Flavour-violating decays of mixed top-charm squarks at the LHC

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Beyond the BSM workshop
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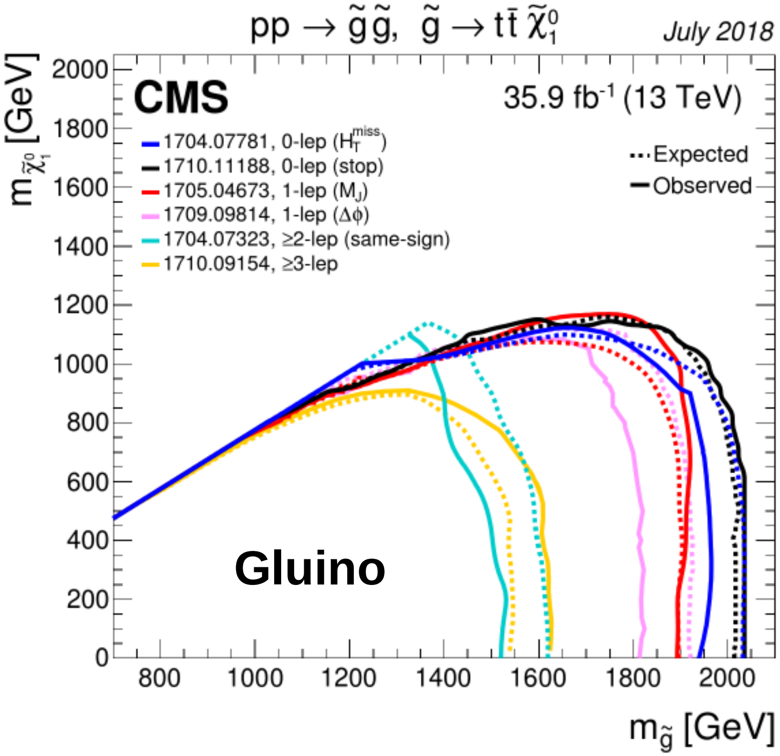
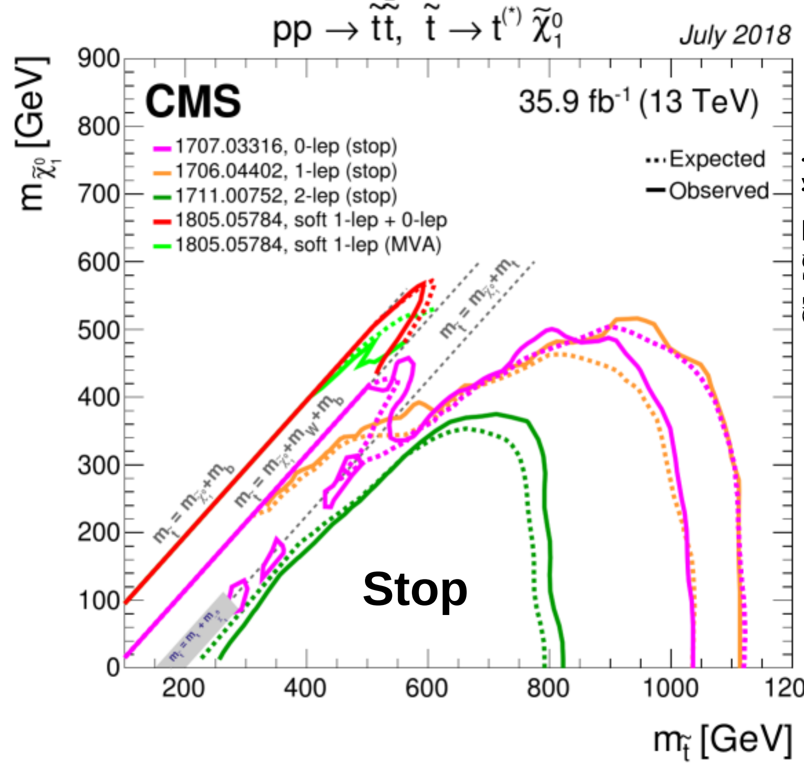
Based on:
AC, Endo, Fuks, Herrmann, Nojiri, Pani and Polesello; hep-ph 1808.07488

Post-Higgs era: SUSY searches



CMS Twiki page



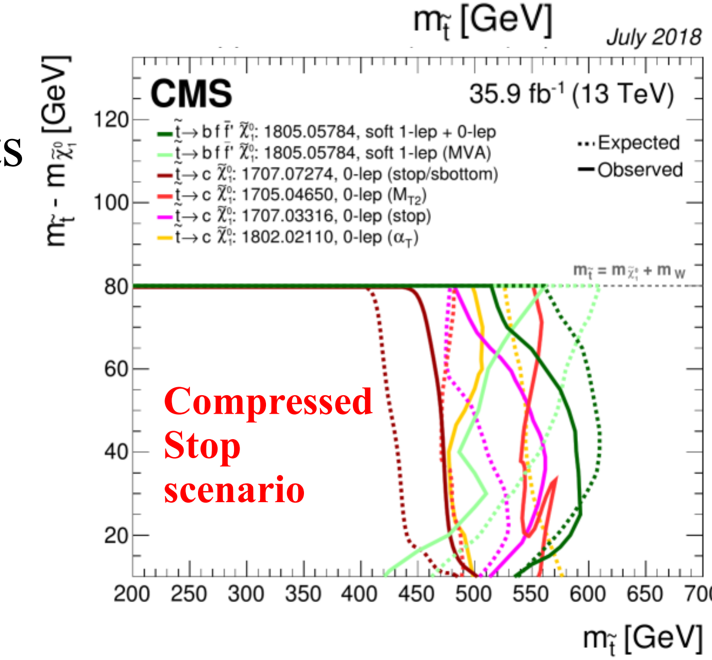
CMS Twiki page

Similar exclusions from ATLAS

– Data consistent with SM predictions; Strong constraints with run-1 and run-2 data, relatively heavy (> 1 TeV)

– **Many assumptions & Limitations ...**

– **Compressed scenario/generation mixing**:
  – light particles (say 500-600 GeV) still possible!
  – **new search strategies**



Flavor in SM

- **Yukawa interaction: only source of FV in the SM**

$$\mathscr{L}_Y = \sum_{i,j=1}^{3} \left(y^e_{ij} \bar{L}_{Li} \Phi e_{Rj} + y^u_{ij} \bar{Q}_{Li} \tilde{\Phi} u_{Rj} + y^d_{ij} \bar{Q}_{Li} \Phi d_{Rj} \right) + \mathrm{h.c}$$

$$Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}_L \sim (3,2,1/3) \qquad U_i = u_{Ri} \sim (3,1,4/3)$$

$$D_i = d_{Ri} \sim (3,1,-2/3) \qquad G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$$

$$L_i = \begin{pmatrix} \nu_{e_i} \\ e^-_i \end{pmatrix}_L \sim (1,2,-1) \qquad E_i = e_{Ri} \sim (1,1,-2)$$

- Quark flavour violating (i.e. charged current) interactions...

$$\boxed{\Gamma_{W^+ d_i \bar{u}_j} \;\propto\; \frac{g_2}{\sqrt{2}} \gamma^\mu \frac{1-\gamma_5}{2} (V_{\mathrm{CKM}})_{ij}}$$

... proportional to Cabbibo-Kobayashi-Maskawa (CKM) matrix

Highly suppressed Off-diagonal terms

$$\boxed{V_{\mathrm{CKM}} \;=\; V_u^\dagger V_d \;\sim\; \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \qquad \lambda \sim 0.2}$$

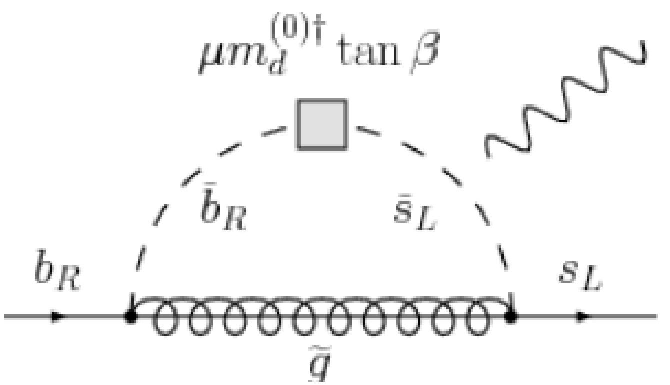
Flavor in MSSM

- Minimal Flavor Violation: Same flavor structure as in SM, Super-CKM basis (squarks undergo similar rotation as quarks), FV effects are proportional to CKM elements
- Beyond MFV: Generation mixing, additional sources of FV

  Direct search: Production and Decay changes significantly, relaxed limits! 

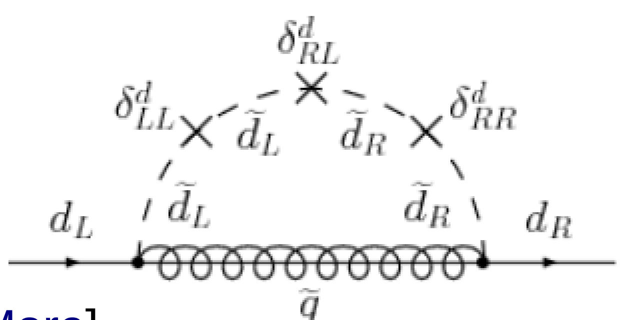
  Strong Limits: low energy flavor data 

$$\boxed{\mathcal{M}^2_{\tilde{u}} = \begin{pmatrix} \mathcal{M}^2_{uLL} & \left(\mathcal{M}^2_{uRL}\right)^\dagger \\ \mathcal{M}^2_{uRL} & \mathcal{M}^2_{uRR} \end{pmatrix}} \qquad (\tilde{u}_L, \tilde{c}_L, \tilde{t}_L, \tilde{u}_R, \tilde{c}_R, \tilde{t}_R)$$



[Higgs data puts limits on LR-type mixing]

- RR-sector (up-type) is almost unconstrained!



[Recent study on non minimal MSSM, global fit, Fuks et. al. JHEP (2015)] [More]

[Gabbini, Masiero (1989); Gabbiani, Gabrieli, Masiero, Silvestrini (1996); Ciuchino, Degrassi, Gambino, Giudice (1998), Lari, Pape, Porod et al. (2008), Fuks et al (2012), Backovic et al (2015), Crivellin et al. (2016) ...]

The Proposal

Mixing in 2^{nd} & 3^{rd} generation RR up-sector:

– Probe lightest mixed state (stop) at the LHC

– **Sensitivity of "tc+missing energy" channel at current & HL LHC.**
(Current Stop searches: tt+ MET, cc+MET)

– Combine search strategies, flavor tagging, probe <u>squark flavor structure</u>, departures from MFV paradigm

Simplified Model

Model:
SM
+ right-handed stop + right-handed scharm
+ Gluino + Neutralino (bino) [Production & Decay]

- Squarks are admixtures of different flavors
- Simplified model: right stop-scharm mixing

$$\begin{pmatrix} \tilde{u}_1 \\ \tilde{u}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{tc} & \sin\theta_{tc} \\ -\sin\theta_{tc} & \cos\theta_{tc} \end{pmatrix} \begin{pmatrix} \tilde{c}_R \\ \tilde{t}_R \end{pmatrix}$$

- 3D parameter space (2 masses, one mixing angle)
  $m_{\tilde{u}_1}, m_{\tilde{u}_2}, \theta_{tc}$

- Possible flavor-violating decays: $\tilde{u}_i \to t + \not{E}_T$ or $c + \not{E}_T$

Signatures:

$pp \to t\bar{t} + E_{\mathrm{T}}^{\mathrm{miss}}$ and $pp \to c\bar{c} + E_{\mathrm{T}}^{\mathrm{miss}}$ $pp \to tc + E_{\mathrm{T}}^{\mathrm{miss}}$

Monte-Carlo set-up

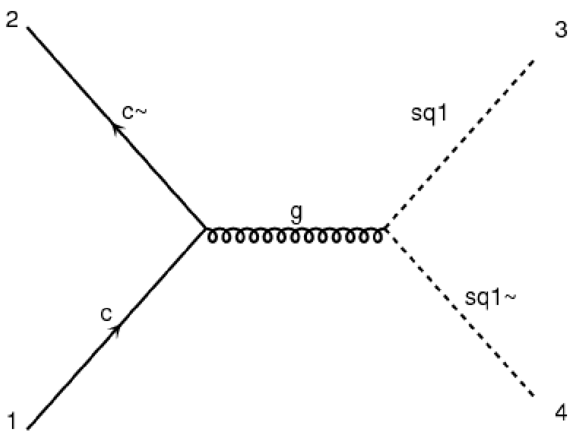


diagram 1 QCD=2, QED=0

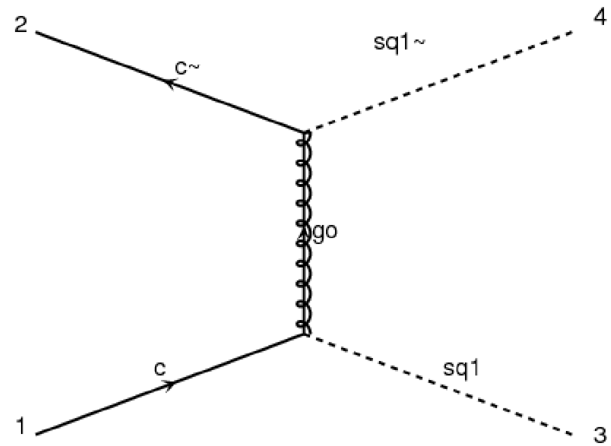


diagram 2 QCD=2, QED=0

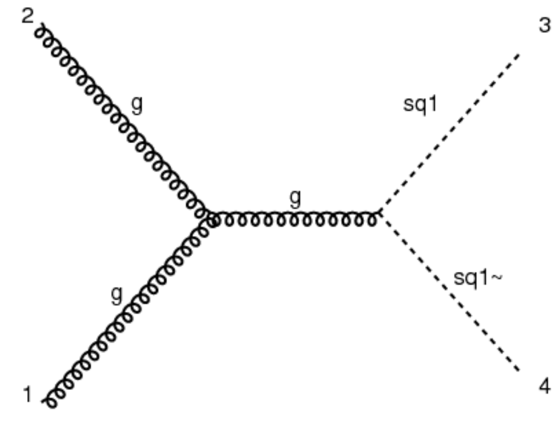


diagram 2 QCD=2, QED=0

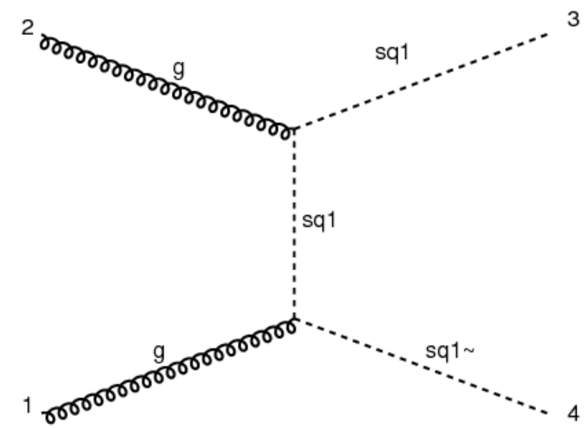
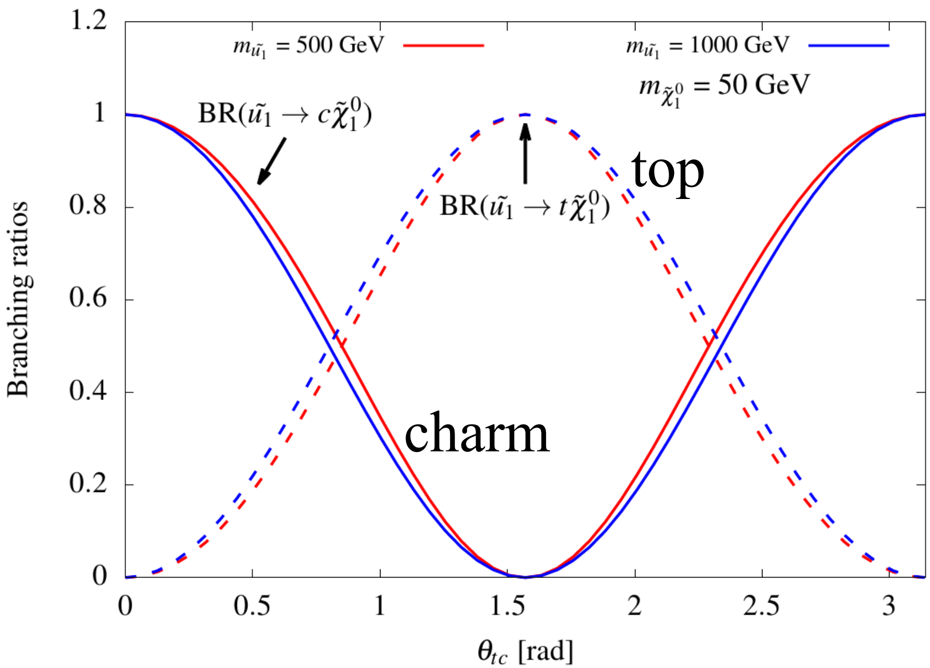
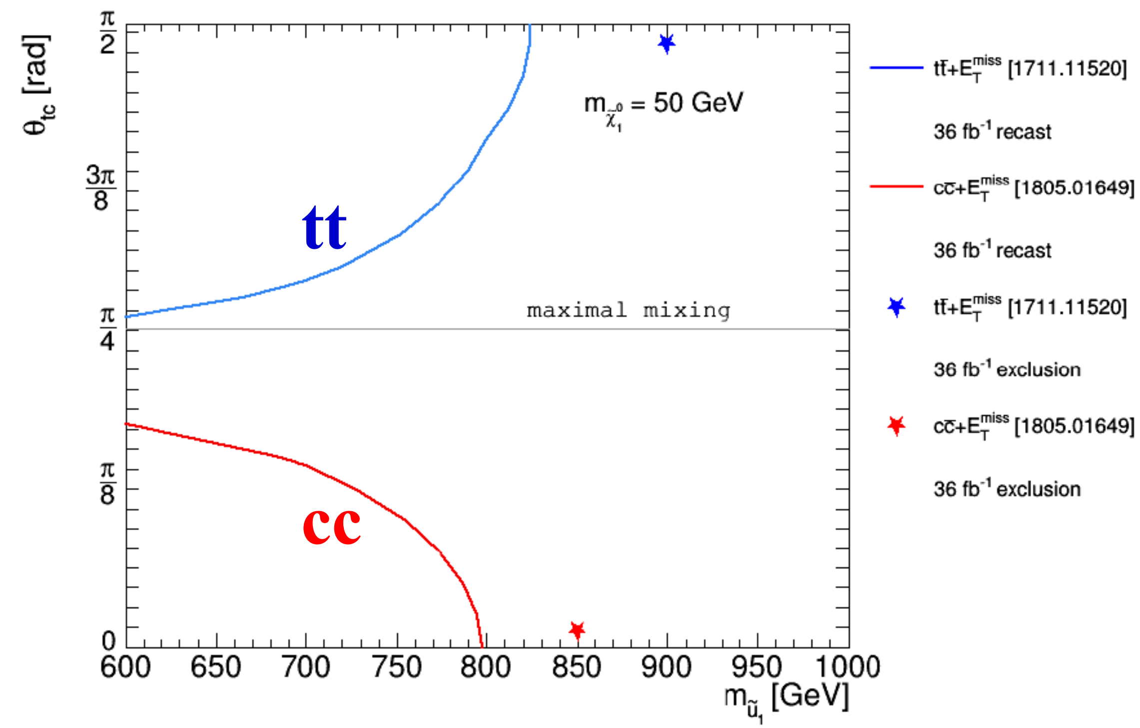


diagram 4 QCD=2, QED=0

- **Signal**: LO using MG5, passed to PY8 and then Delphes; normalized using NLO+NLL xsec
- **Bkg:** ttbar, single top, VV @NLO, ttbarZ, ttbarW, W+jets, Z+jets @LO; PY8 + Delphes; normalized with NNLO/NLO xsecs
- **Squark pair-production:** m(ul) = [600, 1500] GeV, m(chi) = 50 GeV, gluino mass = 3 TeV
- **Jets:** Fastjet with R=0.4, anti-kT, ATLAS card.

Recast of LHC 13 TeV data





- **Scharm search**: ~ 850 GeV @ 13 TeV
- **Stop search**: **1-lepton, jets + MET search at 13 TeV**
- Translate to 3-parameter plane: m(u1), m(u2) and θ (tc).

- **Recast**: compare signal yields with Model independent limits on non-SM contributions from the observed data.

Define: $\mathbf{R = N_{sig} / N_{non\text{-}SM(obs)}}$; R > 1 => **Excluded!**

Event selection – I

Final State : **top + charm + MET**

- Exactly **one lepton** with $p_T > 25$ GeV, $|\eta| < 2.5$.
- At least **one b-tagged jet** with $p_T > 50$ GeV.
- $|\Delta\varphi_{min}(MET, jets)| > 0.6$, $m_T(lep,MET) > 160$ GeV, $m(bjet,lep) < 160$ GeV

$$m_T^{lep} \equiv \sqrt{2\,|\vec{p}_T^{\,\ell}|\,|\vec{p}_T^{\,\mathrm{miss}}|\,(1 - \cos\Delta\phi_{\vec{p}_T^{\,\ell}\vec{p}_T^{\,\mathrm{miss}}})}\,,$$

(Reduces dominant ttbar bkg)

- Two search strategies:

Case-A: Veto additional b-jets ($\varepsilon_b = 77\%$), a light jet with $p_T > 100$ GeV failing b-tagging.

Case-B: Presence of a c-tagged jet ($\varepsilon_c = 30\%$) with $p_T > 100$ GeV and mass > 160 GeV, others with mass > 160 GeV fail b-tagging

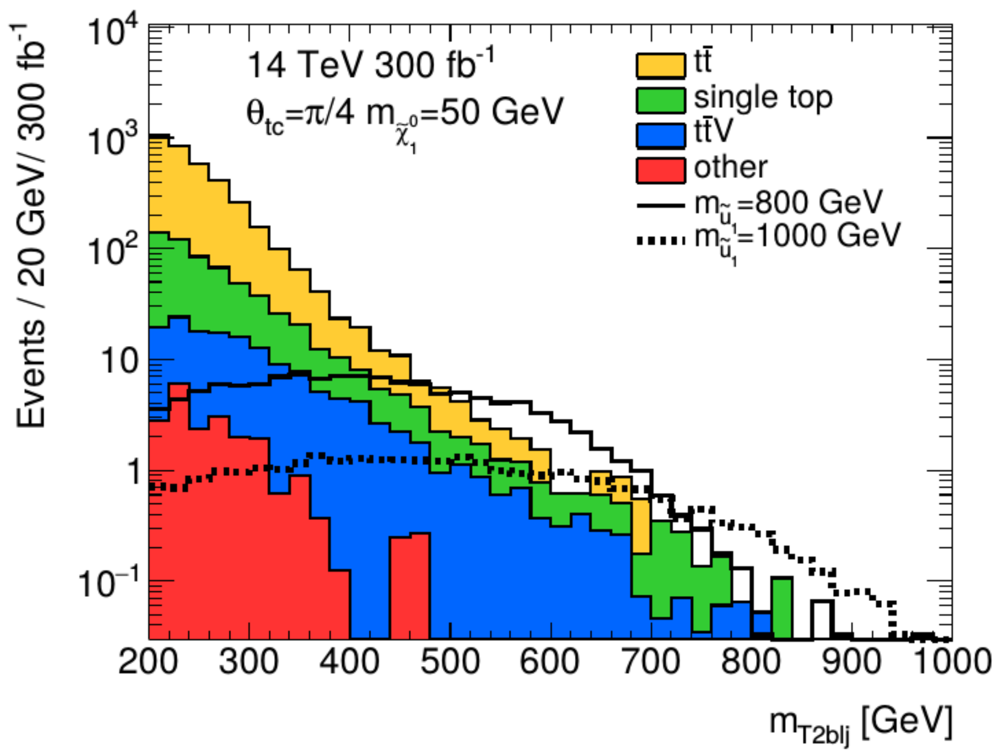
[S/B improves, statistics low]

Event selection - II

- **Asym MT2**: aM_{T2} > 200 GeV (reduce di-lep ttbar)
  (V1 = lepton, b-jet; V2 = remaining leading jet; MET system = (0,80 GeV)
- Presence of a hard c-jet, construct M_{T2}(lep,b-jet,light/c-jet)
  (V1 = lepton, b-jet; V2 = hardest non b-tagged jet (case-A)/c-tagged jet (case-B); MET system = (0,0 GeV)

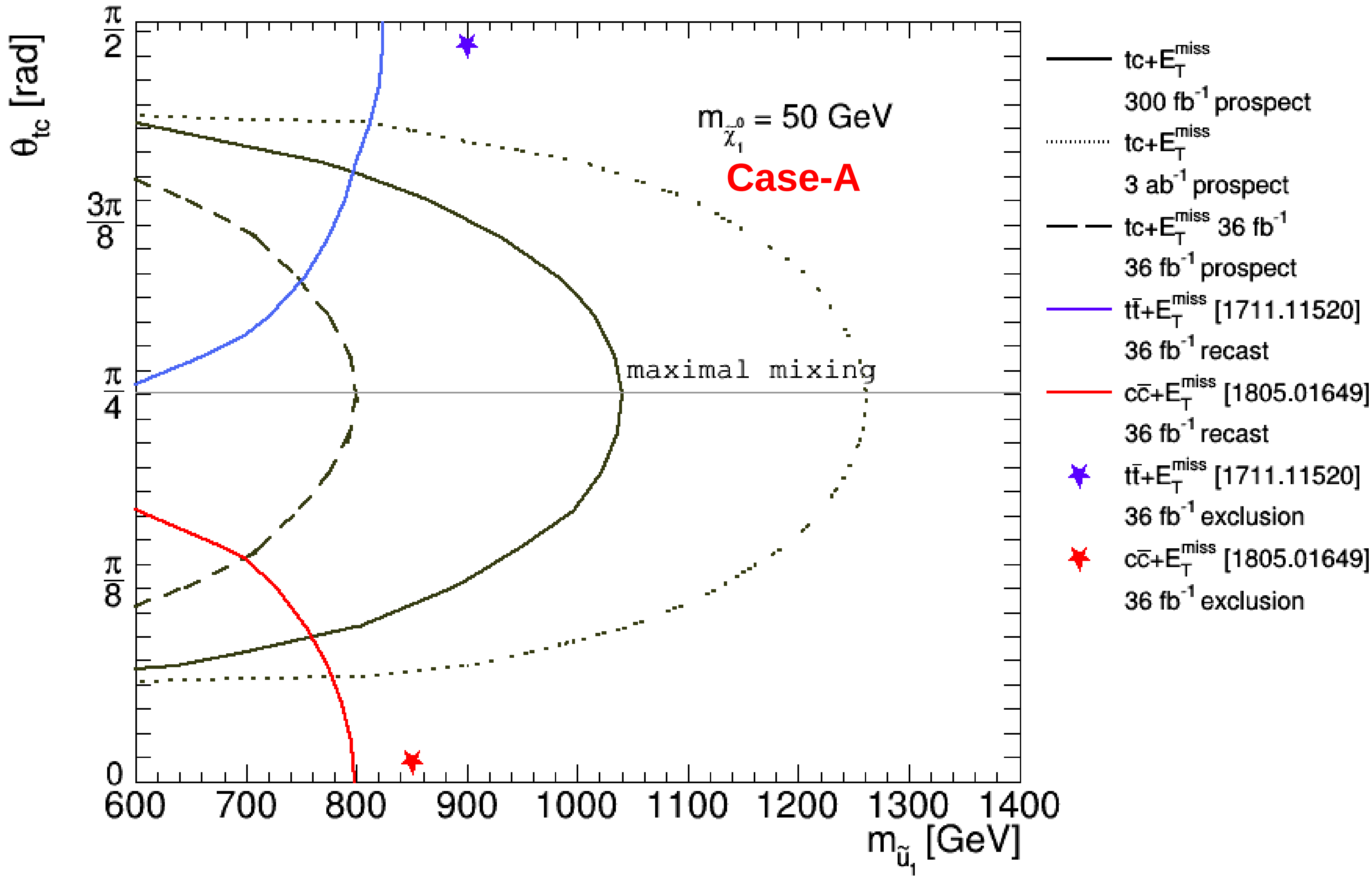
  - Squark mass dependent end-point

$$M_{T2}(\vec{p}_T^{\ell 1}, \vec{p}_T^{\ell 2}, \not{\vec{p}}_T) = \min_{\not{\vec{p}}_T = \not{\vec{p}}_T^1 + \not{\vec{p}}_T^2} \left[\max\{ M_T(\vec{p}_T^{\ell 1}, \not{\vec{p}}_T^1), M_T(\vec{p}_T^{\ell 2}, \not{\vec{p}}_T^2) \} \right],$$



- **Optimize**:
  – depends on squark-neutralino mass splitting
  – vary between [300,600] in 50 GeV

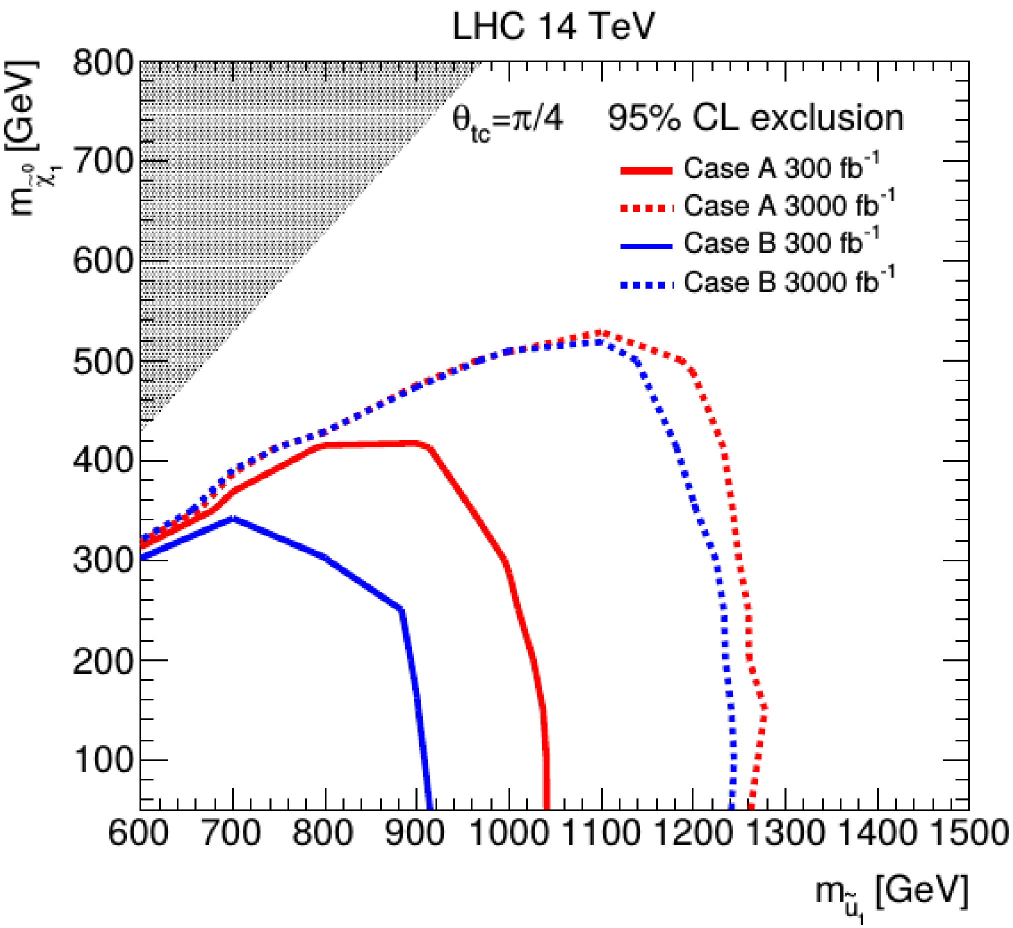
Sensitivity at 14 TeV

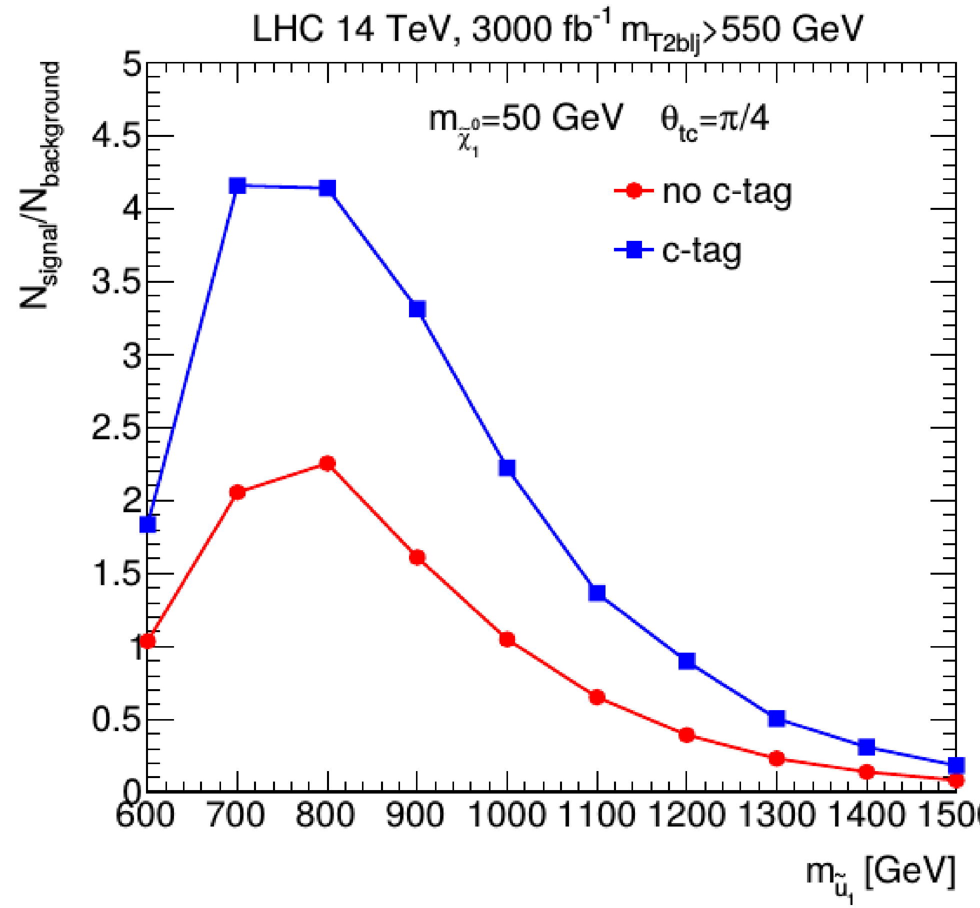


The "tc+MET" strategy:

Probing regions of phase space not accessible with current strategy.

Sensitivity at 14 TeV





– @ High Lumi run, both are comparable, S/B got improved after C-tagging!

Q: After discovery, "mixed stop" originating from t-c or t-u mixing?

- Estimate by <u>changing the c/b-tagging working point, control light jet rejection rates</u>

e.g., for Higgs coupling: Perez et. al. 2015

Summary

– Flavor mixing in right-handed stop and scharm sector, lightest stop is mixed, Interesting collider signatures

– Current strategy excluded stop mass up to 600 GeV, light stop is still viable!

– We study: $t + c + \mathrm{MET}$ topology, two search strategies, core difference inclusion of charm tagging

– Mixed Stop mass up to 1.3 TeV can be probed at High Lumi run of LHC

– Main Advantage:

Combine search strategies, make use of flavor tagging working points, Opens the door to probe squark flavor structure, observation of departures from MFV paradigm

Back ups

Flavor in MSSM

- New sources of FV appears
- Mostly from Soft-SUSY breaking terms (e.g.: gravity mediation, gauge mediation with messenger mixing, …) [Porod et. al.,
- No direct relation with CKM
- Generation mixing at EW scale
- Independent parameters

Non-Minimal Flavor violation

$$\mathcal{M}^2_{\tilde{u}} = \begin{pmatrix} \mathcal{M}^2_{uLL} & \left(\mathcal{M}^2_{uRL}\right)^\dagger \\ \mathcal{M}^2_{uRL} & \mathcal{M}^2_{uRR} \end{pmatrix}$$

6x6

Basis:

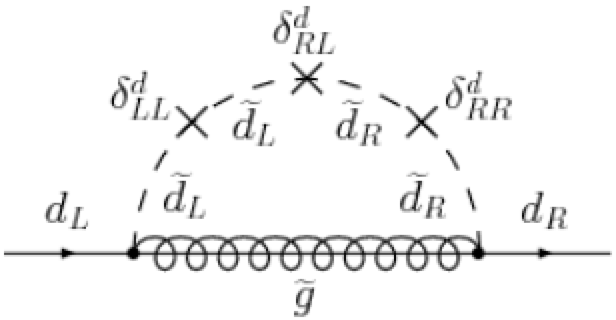
$$\begin{cases} (\tilde{u}_L, \tilde{c}_L, \tilde{t}_L, \tilde{u}_R, \tilde{c}_R, \tilde{t}_R) \\ (\tilde{d}_L, \tilde{s}_L, \tilde{b}_L, \tilde{d}_R, \tilde{s}_R, \tilde{b}_R) \end{cases}$$

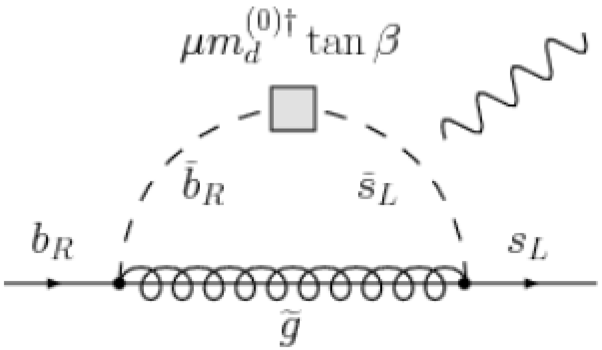
Today $\Rightarrow$

$$\begin{aligned} \delta^{uLL}_{\alpha\beta} &= M^2_{Q,\alpha\beta} \Big/ \sqrt{M^2_{Q,\alpha\alpha} M^2_{Q,\beta\beta}} \\ \delta^{uRR}_{\alpha\beta} &= M^2_{U,\alpha\beta} \Big/ \sqrt{M^2_{U,\alpha\alpha} M^2_{U,\beta\beta}} \\ \delta^{uRL}_{\alpha\beta} &= \frac{v_2}{\sqrt{2}} A_{U,\alpha\beta} \Big/ \sqrt{M^2_{U,\alpha\alpha} M^2_{Q,\beta\beta}} \end{aligned}$$

[Gabbini, Masiero (1989); Gabbiani, Gabrieli, Masiero, Silvestrini (1996); Ciuchino, Degrassi, Gambino, Giudice (1998), Lari, Pape, Porod et al. (2008), Fuks et al (2012), ...]

Consequences of Generation mixing





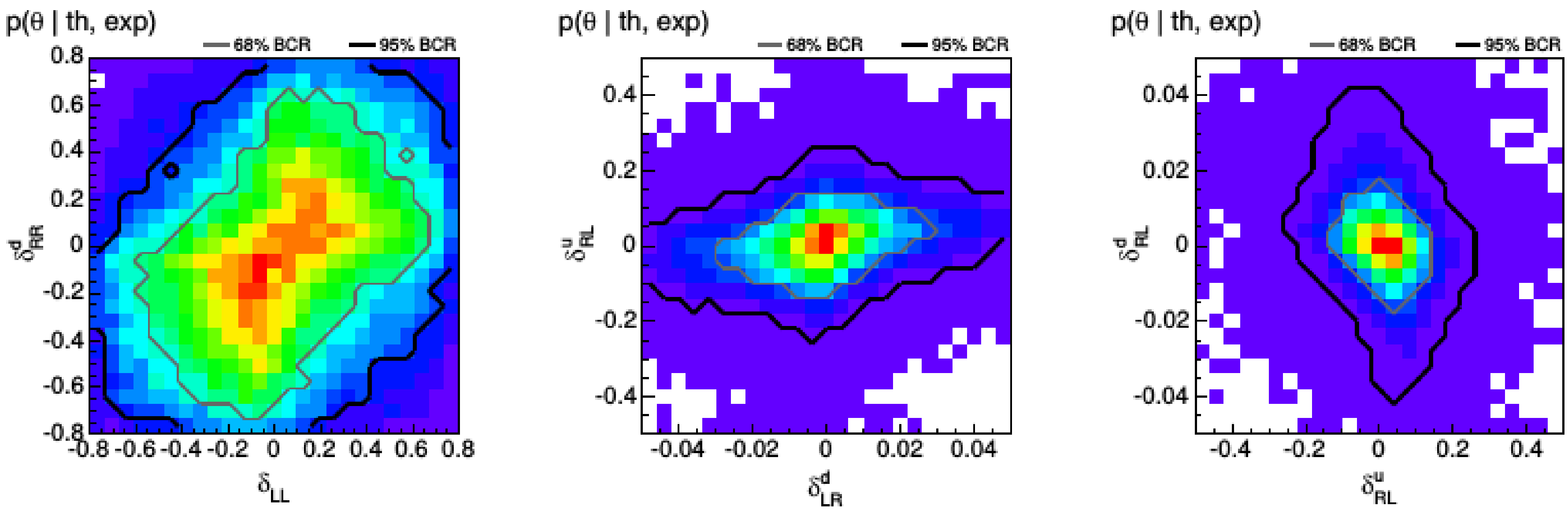


Figure 7. Two-dimensional distributions of the mostly correlated pairs of NMFV parameters after including all constraints.

[Fuks et. al. JHEP (2015)]

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